POLLEN DISPERSAL AND DEPOSITION ON
THE QUELCCAYA ICE CAP, PERU

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Abstract: The relatively young science of tropical ice-core palynology has proven effective in the study of paleoenvironments by its ability to produce long-term and high-resolution paleoclimatic data. However, no studies thus far have investigated the basic dispersal and depositional processes of pollen on these tropical ice caps. In this study, 15 surface snow samples were taken along an east-west transect on the Quelccaya Ice Cap in southern Peru. Results show that pollen assemblages remain fairly uniform across the ice surface, suggesting a uniform mixing of the air mass and its pollen contents over the ice cap. The pollen concentrations, ranging between 17,250 and 55,400 grains/liter, are the highest ever found on a tropical or nontropical ice cap. Concentrations were highest toward the western edge of the ice cap, suggesting that the prevailing winds may have a greater influence on pollen dispersal than other diurnal winds. These results are the first step in understanding the fundamental questions of modern pollen-rain and depositional processes on a tropical ice cap, which are essential for reliable and accurate interpretation of ice-core pollen data. (Key words: Quelccaya ice cap, Peru, ice-core palynology, biogeography.)

INTRODUCTION

To date, ice cores are one of our best-known sources for long-term and high-resolution paleoenvironmental data. Biological as well as abiotic evidence of our past environments is preserved in the glacial ice of polar regions and alpine areas, creating an excellent opportunity for Quaternary paleoenvironmental study through the use of proxy data. The climatic records produced from polar as well as tropical and subtropical alpine ice cores have been well documented in the literature (Dansgaard et al., 1969; Loris et al., 1979; Thompson et al., 1985, 1986, 1989, 1995, 1997, 1998; Oeschger and Langway, 1989; Hammer et al., 1997; Thompson, Mosley-Thompson, and Henderson, 2000; Thompson, Yao, et al., 2000). However, the majority of the data extracted from these cores have been derived from physical or chemical parameters, such as atmospheric dust (Thompson et al., 1988; Cole-Dai et al., 1997, 1999), oxygen isotopes (Thompson et al., 1986, 1995, 1998; Yao et al., 1997; Henderson et al., 1999), and accumulation stratigraphic signatures (Anklin et al., 1998; Van der Veen, Mosley-Thompson, 1999; Van der Veen, Whillans, and Gow, 1999). Although proven to be quite promising, few studies have yet to utilize these ice cores for palynological investigation (Ambach et al., 1966; Lichti-Federovich, 1975a; McAndrews, 1984; Bourgeois et al., 1985, 2000; Bourgeois, 1986, 1990a, 1990b, 2000; Andreev et al., 1997). There are even fewer
palynological studies on tropical and subtropical ice cores (Thompson et al., 1988, 1995; Liu et al., 1998; Yao, 2000). Through these studies, however, it has been shown that sensitive pollen records of past climatic and vegetational changes can be obtained.

Unlike in polar ice caps (Ritchie and Lichti-Federovich, 1967; Lichti-Federovich, 1973, 1975b; Kalugina et al., 1981; Bourgeois et al., 2001), all pollen studies to date on tropical and subtropical ice cores have been conducted without the full understanding of the dispersal and depositional processes on the ice caps themselves. Understanding these processes, in relation to the modern patterns of climate and vegetation, is essential for the interpretation of the fossil pollen signatures being detected within the deeper ice cores (McAndrews, 1984; Bourgeois, 1986, 1990a; Koerner et al., 1988). This, along with the limited numbers of published pollen records (both surface samples and pollen stratigraphies) from the countries of Bolivia (Graf, 1981, 1992) and Peru (Hansen et al., 1984, 1994; Hansen, 1995; Hansen and Rodbell, 1995), has hampered the development of this promising, new science in the central Andes. Currently, there are no data on the patterns and processes of pollen deposition on any high-alpine ice cap. Several studies have been published on high-alpine pollen dispersal (Markgraf, 1980; Jackson, 1991; Fall, 1992; Horn, 1993; Flenley, 1996), however, all of these have dealt with the pollen deposition gradient on mountain slopes and most have stopped short of the summits or any ice cover. This study attempts to utilize 15 surface snow samples, taken on the Quelccaya Ice Cap in late August of 2000, to help answer some basic questions of pollen dispersal and deposition on tropical Andean ice caps.

BACKGROUND

The Quelccaya Ice Cap (13°56' S and 70°50' W; 5670 m above sea level) is located in southern Peru on the eastern side of the Andean Altiplano in the Cordillera Vilcanota (Fig. 1). The ice cap covers more than 55 km² and sits atop a flat ignimbrite plateau (Thompson et al., 1984; Fig. 2). The average annual temperature at Quelccaya is -3°C (Thompson et al., 1985). The annual precipitation around Quelccaya ranges between 700 and 1500 mm per year (water equivalent), or an annual accumulation of snow between 2 and 3 m (Mercer et al., 1975; Thompson and Dansgaard, 1975; Thompson et al., 1984, 1985; Morales-Arnao and Hastingrath, 1999). A strong seasonality exists in the precipitation regime of the area, however, resulting in distinct wet and dry seasons. During the five-month wet season from November to April, the area receives over 80% of its total annual rainfall (Johnson, 1976; Sarmiento, 1986).

Vegetation

The Altiplano, upon which the Quelccaya Ice Cap sits, averages 3700 m above sea level and is dominated by “puna-brava” vegetation (Tosi, 1960). Puna is characterized as a dry grassland, comprised primarily of bunch grasses (Gramineae). Rosette plants, Compositae, cushion plants, and Polylepis trees, along with a host of other xeric shrubs and herbs are also commonly found (Hansen et al., 1984). On
the eastern slopes of the Andes, puna occurs between 3900 and 4300 m (Tosi, 1960; Cabrera, 1968; Cuatrecasas, 1968; Hansen et al., 1984). Above this formation lies another vegetation zone known as the super-puna (4300 m to snowline; Tosi, 1960; Cuatrecasas, 1968; Hansen et al., 1984). The super-puna is primarily dominated by *Plantago*, as well as other herbs and shrubs that are adapted to colder (annually less than 5°C) and drier surroundings (Hansen et al., 1984). Krummholz vegetation adaptations are common among the small trees and shrubs like *Polylepis*, which grows to the edge of the ice cap at Quelccaya. Below the super-puna and puna is a sharp vertical vegetation gradient, which changes from sub-puna (grassland) vegetation to tropical wet forest in a horizontal distance of 200 km in some places. Sub-puna (3300 to 3900 m) is very similar to puna, except that a greater number of trees (especially *Alnus*) are often found (Hansen et al., 1984). Below the three puna zones, humid montane forest (3300–1800 m) and humid subtropical forest (1800–300 m) occur in regions receiving well over 1500 mm of annual precipitation and are usually dominated by trees (e.g., *Podocarpus*), lianas, and ferns (Weerbauer, 1936; Tosi, 1960; Hansen et al., 1984; Young, 1993). Below these areas, where human disturbance has not encroached, tropical wet forest occurs.
On the western slopes of the Altiplano, the vegetation zones are much less complex. This area straddles the rainshadow of the Andes and is dry to only moderately wet all year round. Aspects of the puna grasslands of the Altiplano extend all the way to the western coast of the continent. Although trees such as *Prosopis* are abundant in certain sections of the western coast below 1500 m, they hardly ever form dense stands.

Little is known about the pollination seasonality of central Andean plants. Although year-round pollination is possible (Monasterio and Vuilleumier, 1986), this process is inhibited by frequent precipitation during the wet season and moisture stress during the dry season. Thus for most plants (e.g., *Espeletia*), the height of pollen release occurs in September and October, between the dry and wet seasons (Monasterio, 1986).

**Wind Patterns**

The circulation patterns around Quelccaya and the eastern ridge of the central Andes fall under the influence of the South American summer monsoon (Zhou and Lau, 1998). Winds are typically out of the west for most of the year, but during the austral summer months the winds come primarily from the east and northeast. This dramatic shift in summer circulation is caused by the intense summer heating of the tropical highlands, which forms a warm-core anticyclone over the Altiplano in the upper troposphere. In return, at the lower levels, moist air masses are advected from the east and northeast causing strong convection, condensation, and precipitation. Thus, the resulting latent heat release provides the means by which the warm-core anticyclone is maintained (Schwerdtfeger, 1961, 1976; Gutman and Schwerdtfeger, 1965; Kreuels et al., 1975; Virji, 1981; Zhou and Lau, 1998). This seasonal switch
in the prevailing winds, in conjunction with the diurnal and glacial winds, should have a marked impact on the dispersal of pollen on the ice cap.

METHODS AND MATERIALS

In August (austral winter/dry season) of 2000, 15 surface snow samples from nine different locations were collected along an east/west transect across the ice cap, following the normal summit route from the Quelccaya base camp (Fig. 3). Among these were six pairs of samples taken to test for within-site variability. The two samples within each pair were taken no more than 1 m from each other. For each sample, a small square-nosed shovel was used to collect the snow. Only the top 5 cm of snow were sampled at each site. This uppermost layer should primarily represent accumulation of the current season or year. After collection, the snow was immediately transferred into sealed plastic bags and then allowed to melt naturally. The meltwater was then transferred into leak-proof Nalgene bottles for transport back to Louisiana State University. The amounts of meltwater varied for each sample, but all ranged between 250 to 500 ml. All meltwater samples were processed following the procedure outlined in Liu et al. (1998), which involved the evaporation of the meltwater on a hot plate, down to 100 ml of water. The remaining
sample was spiked with Lycopodium marker spores (Stockmarr, 1972), centrifuged, then treated with acetolysis solution to remove organic matter. The residue was stained and mounted on slides with silicone oil. Pollen grains were identified and counted until a total of 300 grains was obtained, or a minimum of 1000 marker spores was reached. Pollen percentages and concentrations were calculated using the TILIA computer software, and were based on a pollen sum consisting of all pollen grains and spores. TILIA GRAPH was used to generate pollen diagrams for the display of results. Charcoal particles were counted and reported regardless of size, and their concentration values (number of particles per liter of meltwater) were calculated in the same manner as the pollen concentration values.

RESULTS

The results from the pollen analysis show remarkable uniformity among the 15 surface samples (Fig. 4). No significant variations in pollen percentages occur between any of the surface samples, whether paired or individual. Plantago is the most abundant pollen type in nearly all samples, ranging between 19.3% to 27%. This genus of wind-pollinated herbs and shrubs is well represented on the high Altiplano (e.g., Plantago major and P. tubulosa; Gentry, 1993). Alnus (probably A. jorulensis) also is well represented (13.3% to 23%) in the samples. Alnus is abundant in
the sub-puna and humid montane forests between 2500 and 4000 m (Cassinelli, 2000). Other major pollen types include the Urticaceae/Moraceae group, a common montane forest and lowland taxon. These wind-pollinated pollen families are effective in long-distance transport and most likely originate from the eastern Andean slopes. Gramineae (grass) pollen are also common (5.5% to 11%), reflecting the dominance of puna grasses around the ice cap and the Altiplano in general.

Likewise, no significant differences occur between the minor pollen groups. An unknown inaperturate-scabrate pollen is the most abundant among the minor pollen taxa (3% to 12%). This grain resembles *Populus* in size and appearance. Extensive areas of the Altiplano have been planted with exotic species (mainly *Cupressus macrocarpa*, *Eucalyptus globulus*, and *Pinus radiata*), although the presence of *Populus* in the Peruvian Andes cannot be confirmed. Compositae (long-spine or Tubuliflorae-type) are another common minor pollen taxon, ranging from 2.5% to 10%. *Ambrosia*-type (short-spine Compositae) was found in most of the samples, but their abundance is never greater than 2%. The Compositae group of plants can range from small xerophytic shrubs to trees reaching more than 10 m in height (e.g., *Gynoxys oleifolia*), and are well represented on the high Altiplano. The weedy genus *Cuphea* is present in all samples (<2% to 6%), as well as Cupressaceae (<2% to 5%). *Cupressus macrocarpa*, the likely source of Cupressaceae pollen, is a native North American species that is widely planted in the Altiplano and ranges from a shrub in the drier regions to a tree reaching heights of more than 30 m (Cassinelli, 2000). Large areas of *Cupressus* can be found less than 50 km from the ice cap. However, the pollen of this genus is usually underrepresented in pollen assemblages.

Other minor pollen types (ranging from 0% to 3%) include *Polylepis*, a widely abundant tree that can be found in Krummholz form growing in small populations up to the edge of the ice cap. Also present are *Dodonaea viscosa*, another common Altiplano species between 1000 and 3500 m, as well as Ericaceae, *Myrica*, and *Podocarpus*. The latter three taxa are common plants of the humid upper-montane forests located along the eastern slopes of the Andes (3300–1800 m above sea level). Lastly, the miscellaneous pollen category contains pollen from 22 different plant taxa, whose overall abundance does not exceed 2 grains per sample. Of this group, *Weinmannia*, *Cyperaceae*, *Umbelliferae*, *Myrtaceae*, and the Cheno/Am families (Chenopodiaceae and Amaranthaceae) are the most frequent.

The biggest difference among the samples lies in the pollen concentration values. The highest concentrations occur at sites 1 through 6 on the western slopes of the ice cap. These concentrations range between 30,100 and 55,400 grains/l, the highest concentrations found in any tropical or nontropical ice cap. The magnitude of these numbers can only be appreciated when compared to other surface snow samples from around the globe. Surface samples from Greenland and the Canadian Arctic range in pollen concentration from 1 grain/l near the pole to 5280 grains/l in the low Canadian Arctic (Bourgeois et al., 2001). Using the uppermost (modern) levels in Arctic ice cores, McAndrews (1984) reported an average of 7.4 grains/l from the Devon Island ice cap, while similar results (approximately 8 grains/l) were found at the Agassiz Ice Cap on Ellesmere Island (Bourgeois, 1986). In Antarctica, Linskens et al. (1993) reported an average pollen concentration of 0.12 grain/cm³
POLLEN ON THE QUELCCAYA ICE CAP, PERU

(approximately 120 grains/l) from surface moss turfs and cushions. From core-tops in the midlatitudes, Liu et al. (1998) found a pollen concentration of 800 grains/l on the Dunde Ice Cap, while Yao (2000) reported concentration values around 1000 grains/l at the Guliya Ice Cap, both in the Qinghai-Tibetan Plateau, China. It also is important to note that these concentration values from the Quelccaya snow samples are markedly greater than the preliminary work done by Liu on the 1980 Quelccaya ice cores (Thompson et al., 1988). In that study, a pollen concentration of 1600 grains/l was found from one sample, the AD 920 level in the ice core. This raises the question: How does pollen concentration change down an ice core as a function of compaction and ablation? However, this remains an unresolved question at this time.

The lowest concentration values on the Quelccaya surface (17,250 grains/l) occur at sites 7 and 8, the true summit. Similarly low values are found at sites 9, 10, 13, and 14, on the summit dome above 5600 m. Toward the easternmost sites (11, 12, and 15) the concentrations seem to increase slightly again (22,500 to 24,000).

The charcoal concentrations range from 1100 to 6000 particles/l. They tend to follow a similar pattern as the pollen concentrations. The highest values are reached at the western sites, decreasing toward the summit and increasing again at the easternmost sample locations.

DISCUSSION AND CONCLUSIONS

The similarities in the pollen percentages within the samples are most likely a result of uniformly mixed air masses above, and advecting into the ice cap. This is not unexpected, as the high Altiplano is an open, wind-swept environment without many effective barriers. Once over the Andean slopes and on the plateau, winds are allowed to mix freely with each other aided by the strong convective forces characteristic of the region (Schwerdtferger, 1976). However, it also is possible that the homogeneous pollen assemblage is a result of the depth in our sampling. Since our samples were no deeper than 5 cm, it is possible that the entire surface snow layer, and part of its pollen content, was deposited in one or perhaps a few precipitation events.

The most interesting finding thus far concerns the pollen concentrations found among the different surface samples. Winds and advecting air masses are the primary vehicle for the dispersal and deposition of pollen on the surface of an ice cap. Thus, the key to understanding this question lies in the general circulation and microscale wind patterns around the ice cap itself. These samples were collected during the peak climbing season (austral winter/dry season), when the prevailing winds are out of the west. These prevailing westerlies dominate the general circulation and drive the air masses, which are the major source of the pollen brought to the ice cap. Accordingly, the highest concentrations of pollen were found along the western slopes of Quelccaya. However, the microscale, thermally driven mountain winds, which also influence pollen dispersal, are much more complex than this. Though the prevailing winds may deliver the majority of pollen to the ice cap, it is the interplay between the diurnal and glacial winds that unevenly scatter them across the surface.
The glacial wind, or “snow patch wind” (Ohata, 1989a) is a katabatic wind caused by the contrast in temperature between the air in contact with the ice surface and the ambient air adjacent to it (Strenten and Wendler, 1967; Martin, 1975; Manins and Sawford, 1979; Whiteman, 2000). When the air temperature above the ice surface is higher than 0°C, the air layer at the surface will be cooled, resulting in an inversion that starts the katabatic flow (Geiger, 1965; Ohata, 1989b). This nearly constant downhill flow is stronger on sunny summer days with weak upper air winds (Obleitner, 1994) and can be as thick as 100 m (Patagonia Ice Field; Ohata, 1989a), with winds that can exceed 22 m/s (50 mph; Cape Denison, Antarctica; Whiteman, 2000). These should not be confused with the nocturnal katabatic winds, which are a result of a different cooling mechanism. These glacial winds are more prevalent during the summer months, when the temperature inversion is the strongest. However, as long as the air temperature above the ice is greater than 0°C, they can exist 24 hours a day (Geiger, 1965) and all year-round. This wind could significantly impede deposition of an airborne pollen grain on the summit or summit dome, as the wind is constantly pushing these airborne particles off the summit and down the slopes. This could explain the low pollen and charcoal concentrations found at the summit of Quelccaya (i.e., samples 7 and 8). This wind quickly diminishes as it moves down slope and nears the ice’s edge, as the heat release from the land surface around the ice cap warms the air and breaks up the inversion (Whiteman, 1990, 2000). This break in the flow could result in increased deposition of pollen toward the edges of the ice cap on all sides, and help to explain the results we have found in this study.

Another set of thermally driven winds are the daytime upslope (anabatic) and nighttime downslope (katabatic) winds. These diurnal winds are a product of the temperature differences between the air in contact with the slope and the ambient air over the surrounding valley (Whiteman, 1990, 2000; Clements, 1999). During the day, the air over the slope is generally hotter than the air at the same elevation over the valley. This causes the parcel of air over the valley to sink and forces an upslope movement of air. Conversely, at night, the air over the slope loses heat energy more quickly and becomes cooler than the air at the same level over the valley. This in turn causes a shallow downslope current of air. These diurnal slope winds typically range between 1 and 5 m/s (Whiteman, 2000). In a study of the glacier and valley winds at the Hintereisferner (Otztal Alps, Austria), Obleitner (1994) found that the daytime anabatic winds reach the edge of the glacier, but penetrate no further than the tongue before dissipating. This is caused by the inversion layer over the ice surface that will reverse the temperature gradient and weaken the upslope movement. Thus, the pollen-carrying winds would tend to stall over the ice cap’s edge, possibly causing the deposition of the airborne particles they are carrying. This would further explain the greater concentration of pollen and charcoal toward the edges of the ice cap.

Other factors that could increase pollen deposition, especially on the edges of the lee slopes are horizontal roll vortices and vertical axis eddies. Horizontal roll vortices, or rotors, are products of lee-side mountain waves, which form as an air mass is forced over a mountain. They are characterized by very fast and turbulent winds, which rotate in the direction of the general flow and about an axis parallel
to the mountain (Carney et al., 1996; Whiteman, 2000). These winds produce an eddy that can force winds to move upslope and back onto the ice cap. Vertical-axis eddies occur when fast-moving, stable air is forced around a barrier rather than over it. As the wind flows around the mountain, the interior (or mountainside) of the airstream receives more friction as it passes by the barrier (Orgill, 1981). This friction slows down the wind speed and literally turns the airstream back toward the mountain. If the winds are strong and persistent, a continuous spin (eddy) will occur on the backside of the mountain (Forchtgott, 1969), forcing air to return back onto the ice cap, concentrating the pollen toward the edges.

All of these factors, including pollen deposition as a result of precipitation events, work in conjunction with each other to disperse pollen and charcoal in this uneven manner. Despite this emphasis on wind movements, it is important to note that the pollen being transported to the ice cap is not exclusive to that of wind-pollinated species. Insects and insect parts are a common component of glacial ice, and the surface of the Quelccaya Ice Cap is no exception. Insect remains were present in every sample though no significant amounts of pollen from obligatory insect-pollinated species were found.

This study is the first attempt to study the pollen dispersal and depositional processes on tropical ice caps. The results from the paper have answered a few basic questions, but in turn have raised even more. These processes are an essential piece to the puzzle of ice-core palynology. With additional research, some of which is already in progress, the advancement of this science could add another valuable tool for unlocking the mystery of our paleoenvironments.

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